

NUCARS® Wheel/Rail Contact Models and Simulation Results for FRA LD Benchmark

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1. Introduction

In 2005, the U.S. Department of Transportation's Volpe Center proposed a benchmark for a single wheelset simulation to compare how different simulation programs calculate normal contact forces and the effects of flanging with impacts. Transportation Technology Center, Inc (TTCI) has simulated the benchmark cases by using the two wheel/rail (W/R) contact models available in the NUCARS® multibody vehicle/track dynamics simulation program.*

2. NUCARS® Wheel/Rail Contact Models

Two commonly used W/R contact models have been used in the railway industry: (1) the rigid W/R contact model and (2) the penetration contact model.^{1,2} Both models are available for TTCI internal NUCARS users. Only the rigid contact model is generally available to all NUCARS users, although the penetration contact model in NUCARS is expected to be released to all users soon.

Creep forces in both W/R contact models are calculated using Kalker's fully non-linear creep theory, through lookup tables of W/R creep coefficients.³ The W/R creep coefficient tables have been calculated using Kalker's programs CONTACT and DUVOROL. The creep force calculations also require a non-zero value for W/R friction.

The penetration contact model has been used for all the benchmark simulations. A limited number of the requested benchmark simulations have been conducted with the rigid contact model. Detailed results for each of the simulation cases have been attached. Some sample results are discussed in the following sections.

2.1 NUCARS® Standard Rigid Wheel/Rail Contact Model

The standard rigid W/R contact model in NUCARS evolved from the rigid W/R contact models used in steady state curving models developed in the 1970's and early 1980's. Contact geometry tables are pre-calculated to describe the geometric constraints and contact patch shape parameters of the W/R contact.

NUCARS treats the W/R contact as a specialized connection element. Each W/R connection element includes vertical and lateral springs and dampers to represent the track stiffness and damping, including the effects of W/R contact stiffness. The rails are not provided with mass or inertial properties. During each integration step, these stiffness and damping values are used by NUCARS in the initial calculation of the normal forces between the wheels and rails. Final values of normal force at each

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integration step are derived through an iterative process, together with calculation of the W/R creepages and creep forces. The algorithms accommodate complete wheel unloading.

This formulation requires that the “rail” stiffness and damping values remain finite and within reasonable bounds. Otherwise, the simulation will suffer from integration instability. Unreasonably high values of stiffness in relationship to the wheelset mass require very small integration time steps. The very stiff rails specified in the benchmark resulted in considerable difficulties with integration instability and two-point contact “chatter” for many of the exercises. However, experience has shown that values of stiffness and damping that correspond to realistic values found in actual practice provide good correlation to other simulation models and test results of actual vehicles.⁴

The standard W/R contact model can accommodate two points of contact between each wheel and rail, including contact between flange back and guard/restraining rails. Wheel profiles may be different on each wheel of a vehicle. The rail profile may be varied along the track by interpolation of W/R contact geometry files.

2.2 NUCARS® Wheel/Rail Penetration Contact Model

TTCI has developed a real-time (on-line) W/R contact model that will soon be available as a second option for use in NUCARS.⁵ This extends the simulation capability of NUCARS to include the complicated modeling of a complex flexible track structure, including dynamic rail rotations and profile variations along the track. These are difficult to model using the rigid W/R contact model in the standard version of NUCARS.

The new on-line W/R contact model uses a new multi-point penetration algorithm. As shown by the solid lines in Figure 1, contact is simulated by separating the contact patch into several single elliptic contact patches. The centers of pressure for each of the ellipses are determined by the penetration function between the wheel and rail profile shapes. Now, as the wheelset moves slightly relative to the rails, the overlapping ellipse patches are each allowed to change shape resulting in a more realistic representation of the actual contact patch shape and more gradual variations in contact force. Each of the contact patches may be separate or may overlap, as shown.

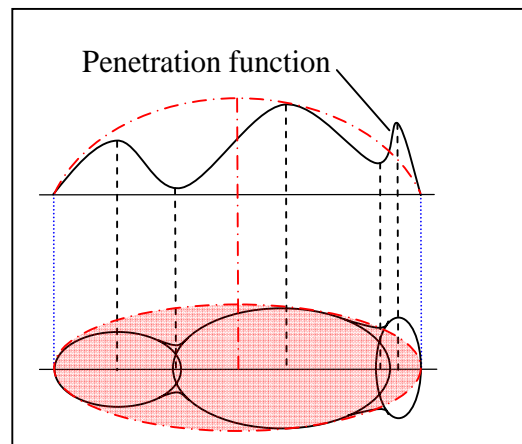


Figure 1. Multi-Point Non-Elliptical Contact

NUCARS treats the W/R contact as a specialized connection element. In the case of the penetration model, the positions of the rails and wheels at the beginning of each integration step are identified, and the corresponding W/R penetrations are calculated. Normal forces from the W/R contact are derived from these penetrations, together with

calculations of the W/R creepage and creep forces. The algorithms accommodate complete wheel unloading.

As with the rigid contact model, this formulation requires that the rail stiffness and damping values remain finite and within reasonable bounds. Otherwise, the simulation will suffer from integration instability. Unreasonably high values of stiffness in relationship to the wheelset mass require very small integration time steps. However, it has been found that the penetration model is generally much less sensitive to integration instability than the rigid contact model.

This new W/R contact model includes a method for varying rail profile shape along the track. Inputs to the NUCARS program are the wheel and rail cross-section profile shapes. The W/R penetration model also permits optional use of a new multibody flexible track simulation model in NUCARS. The penetration contact model and the new flexible track model capability have been validated through comparisons with the benchmark results of test results and other simulation packages.^{6,7}

3. Penetration Model Benchmark Simulation Results Analysis

The benchmark specifies that the rail suspension to the ground is rigid. In NUCARS, finite values of stiffness and damping must be used for the modeling of the track structure elastic properties. The stiff suspension parameters listed in Table 1 are used in the benchmark.

Table 1. Rail Suspension Parameters

Parameters	Case 1	Case 2
Lateral Stiffness(N/m)	1.75E+10	1.75E+10
Lateral Damping(Ns/m)	5.25E+04	1.75E+06
Vertical Stiffness(N/m)	1.75E+10	1.75E+10
Vertical Damping(Ns/m)	3.68E+07	8.93E+06

The benchmark requests the output of wheelset kinetic and potential energy. Due to the introduction of rail support damping in NUCARS, the benchmark is not a conservative system. The NUCARS energy output result includes the kinetic and potential energy and the consumption energy of rail support dampers. However, the potential energy of W/R penetration contact was not included. Because the W/R contact stiffness is nonlinear, the potential energy has to be integrated according to its nonlinear characteristic. But, the contact stiffness characteristics, which depend on the W/R contact point geometry, can not be determined at each integration step during the simulation. The flange contact penetration, which is much bigger than that on tread during impacts, leads to a higher potential energy. Because this part of the potential energy was not included, the energy correspondingly decreased sharply during flange contact, as Figure 2 shows. Figure 3 shows the right wheel flange contacts on the rail with large penetration, but with no contact on the left side at the moment of 0.0415s.

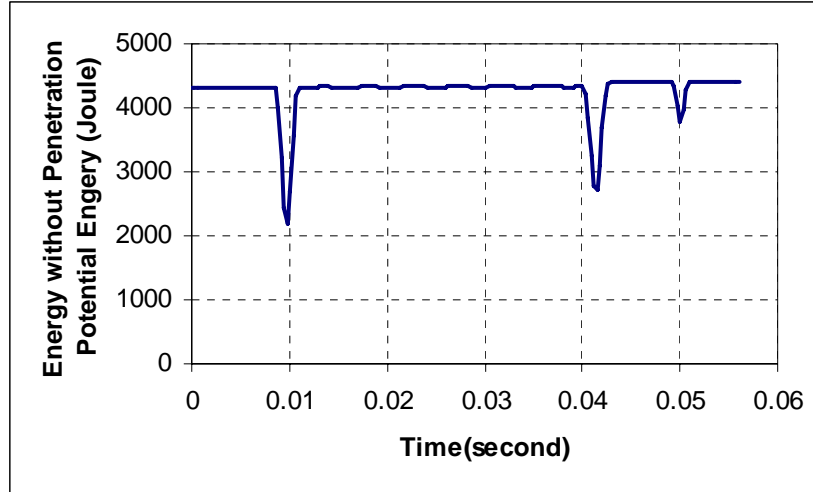


Figure 2. Kinetic and Potential Energy (Case1, Exercise 4, swprof/srprof)

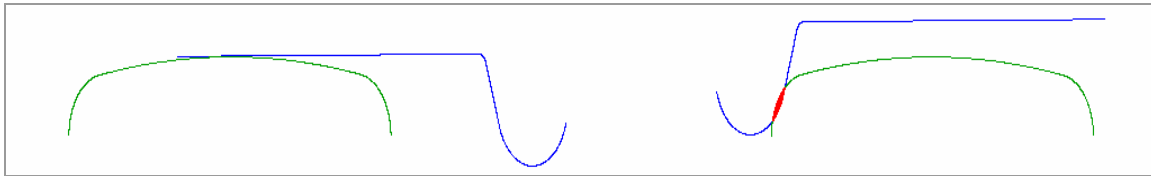


Figure 3. W/R Interaction at t=0.0415s(Case1, Exercise 4, swprof/srprof)

4. Comparison between Penetration and Rigid Contact Model

Both NUCARS W/R contact models require the input of the W/R element stiffness and damping. As discussed in subsection 2.1, for the rigid contact model, the stiffness and damping are generalized parameters including both the W/R contact patch and rail support stiffness and damping. For the penetration contact model, the W/R element stiffness and damping comes from the rail support structure, including the ties, fasteners, and ballast. The W/R contact patch stiffness is not included. This is provided either as a generalized stiffness and damping, or it comes from a full multibody model of the track structure.

Some of the benchmark simulations were also conducted by using the rigid contact model in the standard version of NUCARS. But instead of using the stiffness and damping values from the penetration model (Table 1), the following values were used for the rigid contact model:

- Lateral and vertical stiffness was $2.63\text{E}+09$ N/m
- Lateral and vertical damping was $5.25\text{E}+04$ Ns/m.

Figure 4 shows the displacement comparisons for the swprof/srprof theoretical wheel/rail pair at 1 m/s initial velocity (Case 1, Exercise 3). The displacement amplitude and phase of rigid contact model are similar to that of the penetration model. However, the amplitude and duration of the W/R forces are quite different, as Figure 5 shows. It is expected that different choices in stiffness and damping values would result in different peak impact forces for both W/R contact methods.

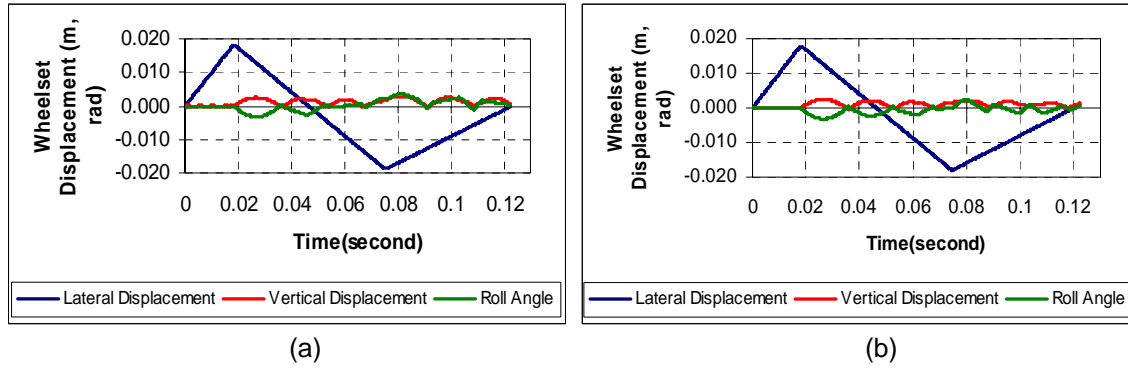


Figure 4. Displacements of Penetration (a) and Rigid (b) Contact Models

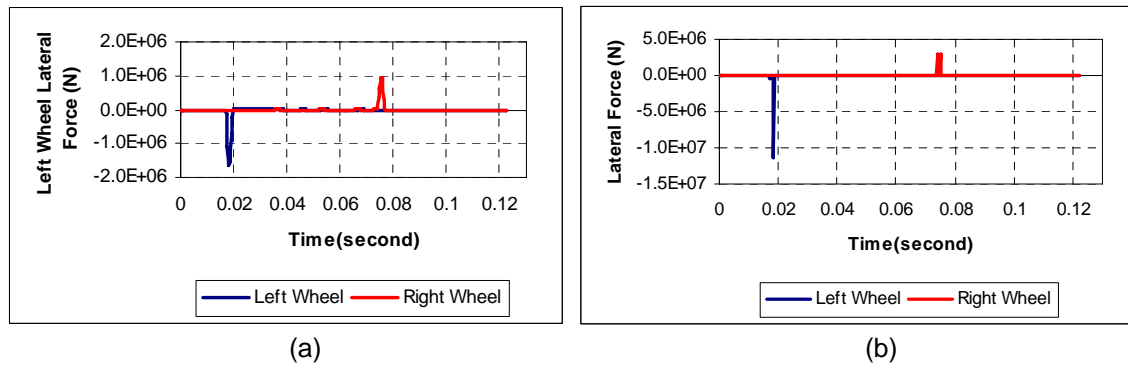


Figure 5. Wheel Lateral Forces of Penetration (a) and Rigid (b) Contact Models

5. Conclusions and Recommendations

The benchmark simulations show the NUCARS W/R penetration contact model is capable of simulating wheel lift, W/R two-point contact and impact, flange climb, and derailment cases.

The W/R contacts of the two W/R profile combinations in this benchmark are typical hertz contact cases; the non-hertz contact cases were not tested. The following suggestions, including the non-hertz contact cases, are recommended for the evaluation of robust W/R contact models:

- Simulation of measured worn conformal W/R profiles with at least 75-degree flange angle
- Simulation of guard rail with flange back contact
- Output of three-dimensional W/R contact geometry
- Realistic track stiffness and damping values
- Comparison to measured wheel/rail forces

Practical applications of W/R contact models will usually have much lower vertical and lateral track stiffness values than requested for this benchmark. Realistic values of track damping will also result in significant energy dissipation. To make a realistic evaluation of different methods of W/R contact simulation, these effects should be included and simulation results compared to accurate measurements of W/R dynamic response.

References

1. Iwnicki, S., 1999, "The Manchester Benchmarks for Rail Vehicle Simulation," *Vehicle System Dynamics*, Vol. 31, Lisse, Netherlands.
2. Kik, W., 1990, "Comparison of the Behavior of Different Wheel_Track Models," *Proceedings of the 12th IAVSD Symposium on the Dynamics of Vehicles on Roads and Track*, Sauvage, G., (ed), Lyon, France.
3. Kalker, J.J., 1979, "The Computation of Three Dimensional Rolling Contact with Dry Friction," *International Journal for Numerical Methods in Engineering*, Vol. 14, pp. 1293-1307.
4. Wilson, N.G., and S. G. Gurule, March 1997, "Application of Instrumented Wheelset Technology to Transit System Research and Development," ASME-IEEE Joint Rail Conference Boston, MA.
5. Xinggao Shu, Nicholas Wilson, Charity Sasaoka, and John Elkins, August 2005, "Development of a Real-Time Wheel/Rail Contact Model in NUCARSTM and Application to Diamond Crossing and Turnout Design Simulations," *Proceedings of the 19th IAVSD Symposium on the Dynamics of Vehicles on Roads and Track*, Milan, Italy.
6. Elkins, J.A., B. Brickle, N. G. Wilson, S. Singh and H. Wu, August 2001, "Track Structure Modeling with NUCARSTM and Its Validation," *Proceedings of the 17th IAVSD Symposium on the Dynamics of Vehicles on Roads and Track*, Lyngby, Denmark.
7. Steffens, D., and M. Murray, June 2005, "Establishing Meaningful Results from Models of Railway Track Dynamic Behaviour," *Proceedings of the 8th International Heavy Haul Association (IHHA) Conference*, Rio di Janeiro, Brazil.